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High repetition frequency laser on self-terminating calcium ion transitions

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The results of experimental studies of the parameters of laser on self-terminating calcium ion transitions with $\lambda_1 = 854.2$ nm and with $\lambda_2 = 866.2$ nm under the excitation by pulses with nanosecond edges are presented. In the burst operation mode the average power of 5.3 W was obtained at a pulse repetition frequency of 90 kHz with lasing efficiency of $\sim 0.076\%$. It is demonstrated that at high pulse repetition frequency the specific energy of the laser are not inferior to the values of lasers on self-terminating transitions of the copper atom with a comparable volume of the active medium.

Keywords: laser, calcium, self-terminating transitions, laser oscillation, pulse repetition frequency.

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Although gas-discharge lasers on self-terminating transitions (transitions from resonance levels to a metastable one, RM transitions), primarily in copper atoms and nitrogen molecules, have a long history of study and application, they still attract research attention due to a number of unique characteristics: high active medium gain, small lasing line width, high beam quality, high pulse power, etc. One promising direction is their application in brightness multiplication systems, which provide an opportunity to perform remote monitoring of high-speed processes under intense background illumination [1]. Real-time imaging places certain demands on active media. One of them is the capacity of laser sources and power (brightness) amplifiers to be operated in the pulsed mode with pulse repetition frequency f that is as high as possible. Copper (or copper salts) vapor lasers are used most often for this purpose; the provide a power of several watts at pulse repetition frequencies up to a hundred kilohertz [2–5].

Several fundamental constraints are imposed on the repetition frequency of a copper vapor laser. The most significant of them are the enhancement of parasitic channels of population of lower metastable states [6] and the skin effect [7]. Both these phenomena grow weaker as diameter d of working gas discharge tubes (GDTs) and the specific pumping energy decrease, thus inducing a reduction in average lasing power P_{av}.

A significant increase in lasing power P_{av} with the GDT diameter remaining unchanged at $d = 1-2$ cm may be achieved by reducing the duration of the leading edge of a pumping pulse [8]. Switching devices with a switching front on the order of several nanoseconds provide an opportunity to generate high-voltage pulses with nanosecond edges and use them for the excitation of lasers on self-terminating transitions. This provides an opportunity not only to improve the frequency-energy characteristics of lasers, but also to find novel design solutions for lasers on self-terminating transitions (by virtue of the possibility of operation at higher ion concentrations). Although the list of promising media is fairly long [9], lasers on RM transitions in ions are less advanced than lasers on RM transitions in atoms an molecules, which have been characterized in a great number of papers and several monographs. It was demonstrated in [10] in experiments with a self-terminating barium ion (Ba II) laser (transition $6p\,^2P_{3/2}-5d\,^2D_{5/2}$, $\lambda = 614.2$ nm) that its average lasing power ($f \approx 60-70$ kHz) increases considerably under excitation with high-voltage pulses with an edge duration of 2–3 ns shaped by a switching device of a novel type called an eptron [11]. This device, which relies in its operation on self-breakdown of a discharge in a capillary with a plasma cathode, is characterized by switching times down to $\tau_s < 1$ ns and a pulse compression at the level of $S = \tau_d/\tau_s = 10^3$ at pulse repetition frequencies at least up to $f \approx 100$ kHz (τ_d is the discharge development delay).

The aim of the present study is to examine the lasing parameters of a laser on self-terminating calcium ion transitions $4p\,^2P_{3/2}-3d\,^2D_{5/2}$ with $\lambda_1 = 854.2$ nm and $4p\,^2P_{1/2}-3d\,^2D_{3/2}$ with $\lambda_2 = 866.2$ nm at high (up to $f \approx 100$ kHz) pulse repetition frequencies. This laser has already demonstrated the highest average power P_{av} and efficiency of lasing within the entire class of RM lasers on ion transitions. The maximum power achieved in [12] was $P_{av} \approx 0.74$ W with specific lasing energy $w_{sp} \approx 0.62\,\mu$J/cm^3 at an efficiency of 0.05% at $f = 6.85$ kHz. The values of $P_{av} \approx 0.3$ W and $w_{sp} \approx 0.28\,\mu$J/cm^3 were demonstrated in [13] with frequency-energy dependence $P_{av}(f)$ having an extremal nature with a maximum at $f \approx 17.8$ kHz.

A beryllium oxide gas-discharge tube, which was characterized in detail in [10], was used in our experiments. The working diameter of the GDT channel was $d = 1.5$ cm, the discharge gap length was 55 cm, and the volume was 97 cm^3. The pressure of buffer (helium) gas was

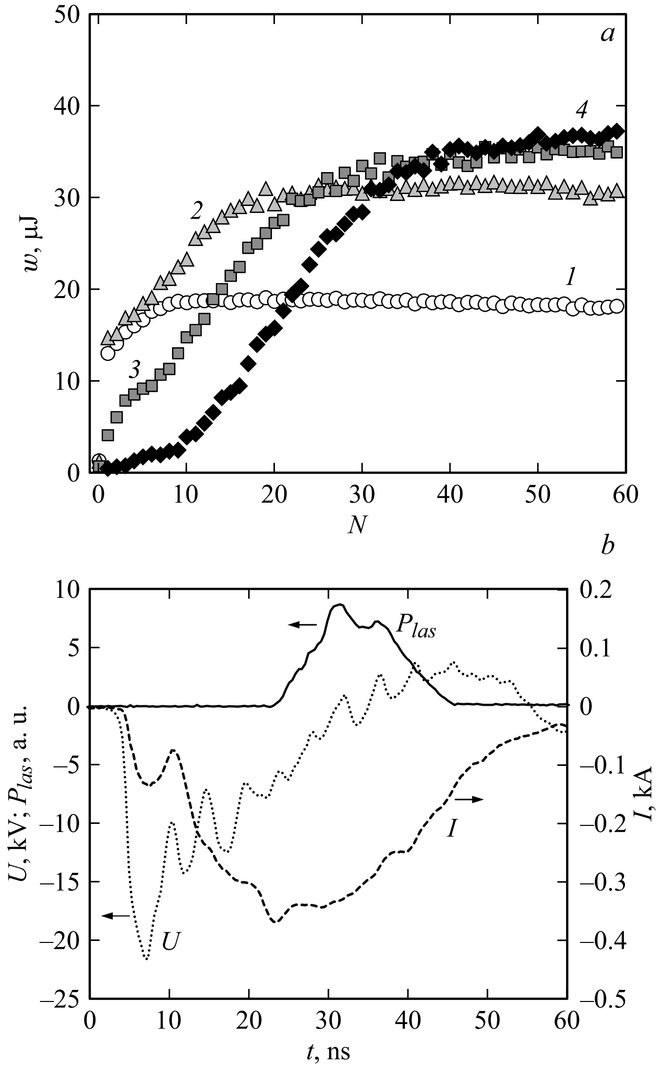

Figure 1. a — Energies of lasing pulses w in a train (N is the pulse number) at pulse repetition frequencies $f = 20$ (*1*), 40(*2*), 60 (*3*), and 80 kHz (*4*). b — Oscilloscope records of voltage pulses at the GDT U, current through the GDT I, and lasing power P_{las} in steady operation at $f = 60$ kHz. $U_a = 22.5$ kV, $p = 10$ Torr, and $T = 700^\circ$C.

$p = 10-40$ Torr. A resistive heater was used to adjust the GDT temperature and, consequently, the pressure of calcium vapor. The medium was excited upon direct discharge of an optimized working capacitance $C = 330$ pF through an eptron and the GDT by pulse trains with a repetition frequency of 0.5 Hz that contained 200 pulses (pulse repetition frequency $f = 10-100$ kHz). The optical laser cavity was formed by a nontransmitting spherical mirror with a radius of 5 m for the region of lasing wavelengths and a quartz plane-parallel plate (the reflection coefficient was 99.5 and 8%, respectively). The lasing energy and power were measured with an FK 32 vacuum photodiode with a time resolution better than 1 ns. A Thorlabs S401 power meter was used for calibration.

Figure 1, a shows radiation energy w as a function of pulse number N in a train at pulse repetition frequencies $f = 20$, 40, 60, and 80 kHz. It can be seen that the radiation energy stabilizes by the 40th pulse and remains almost unchanged to the end of the train. Thus, it can be said that a quasi-steady regime was established. When the maximum lasing power was achieved, the ratio of radiation energies w_1 and w_2 at $\lambda_1 = 854.2$ nm and $\lambda_2 = 866.2$ nm, respectively, was $w_1/w_2 \approx 1.7$. Oscilloscope records of voltage pulses at the GDT U, current I through it, and a lasing pulse in steady operation (the 41st pulse) at $f = 60$ kHz are presented in Fig. 1, b. The typical GDT voltage buildup time was $\tau_U \approx 1.5$ ns. The oscilloscope record of current has two components. The first peak with a FWHM of $\sim 3-5$ ns

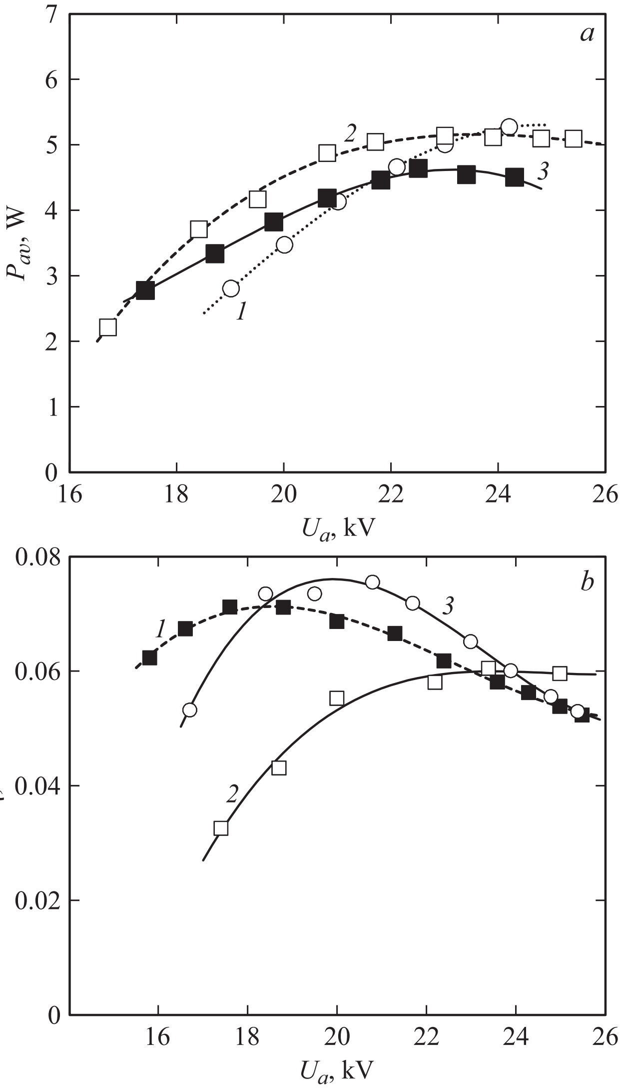

Figure 2. a — Dependences of average lasing power P_{av} on peak working capacitance voltage U_a at different buffer gas (helium) pressures: $p = 10$ (*1*), 20 (*2*), and 40 Torr (*3*). $f = 90$ kHz, $T = 700^\circ$C. b — Dependences of lasing efficiency η on peak working capacitance voltage U_a. *1* — $f = 50$ kHz, $p = 10$ Torr, $T = 680^\circ$C; *2* — $f = 50$ kHz, $p = 10$ Torr, $T = 700^\circ$C; *3* — $f = 90$ kHz, $p = 20$ Torr, $T = 700^\circ$C.

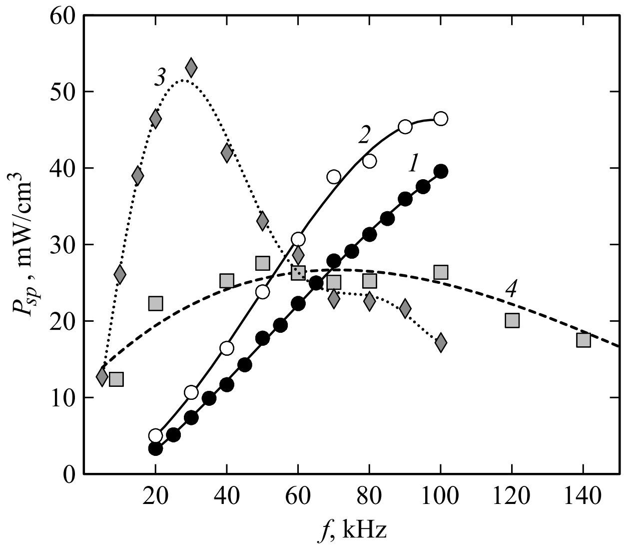

Figure 3. Dependences of specific average lasing power P_{sp} Ca^+ laser at $p = 10$ Torr (*1* — $U_a = 17.5$ kV, $T = 680°$C; *2* — $U_a = 22.5$ kV, $T = 700°$C) and copper bromide vapor lasers [14] (*3*) and [5] (*4*) on pulse repetition frequency f.

corresponds to charging of the intrinsic GDT capacitance. Lasing always developed around the maximum of the second current peak with $\tau_I \sim 20-25$ ns and persisted for $\tau_{las} \sim 10-12$ ns (at half height) in steady operation. Depending on the conditions (pulse repetition frequency in a train f and initial voltage U_a at working capacitance C), the optimum GDT temperature was $T = 700 \pm 5°$C at helium pressure $p = 20 \pm 5$ Torr. Figure 2, *a* shows example dependences $P_{av}(U_a)$ of the average lasing power on the operating voltage amplitude at frequency $f = 90$ kHz, temperature $T = 700°$C, and helium pressures $p = 10$, 20, and 40 Torr. It is evident that the optimum pressure corresponding to the maximum of average lasing power $P_{av} > 5$ W does not exceed $p = 20$ Torr at the used voltages $U_a = 22-25$ kV. Figure 2, *b* presents example dependences $\eta(U_a)$ of the lasing efficiency (ratio of the lasing energy to the energy stored in the working capacitance) on the voltage amplitude at $f = 50$ and 90 kHz, helium pressure $p = 10$ and 20 Torr, and various GDT temperatures. The maximum lasing efficiency calculated with respect to the energy stored in working capacitance C, was $\eta \approx 0.076\%$ and corresponded to $U_a = 19-21$ kV, $f = 90$ kHz, $p = 20$ Torr, and $T = 700°$C. It follows from the oscilloscope records of voltage and current pulses that approximately one half of the energy stored in C goes into the GDT.

Figure 3 shows example dependences $P_{sp}(f)$ of the specific average lasing power on the pulse repetition frequency at $p = 10$ Torr and different values of amplitude U_a and temperature T (curves *1* and *2*). Similar dependences for CuBr lasers with active media 157 and 404 cm^3 in volume (curves *3* and *4*; the data were taken from [14] and [5], respectively) are also shown for comparison. It is evident that the specific self-terminating lasing power of the calcium ion laser increases linearly with increasing pulse repetition frequency and does not reach saturation through at least to $f = 100$ kHz (the limit operation frequency of the excitation generator). Starting from $f > 50-60$ kHz, it exceeds the specific lasing power of copper bromide vapor lasers.

Thus, it was demonstrated experimentally that the excitation of ion lasers based self-terminating ion transitions (with a calcium ion laser used as an example) by high-voltage pulses with nanosecond edges results in expansion of the operating frequency range (the maximum pulse repetition frequency $f = 100$ kHz in our experiments was limited by the generator parameters) and an increase in the lasing power. Notably, the specific energy characteristics of the laser are higher than those of a laser on self-terminating copper atom transitions at high pulse repetition frequencies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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